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Experimental investigations on the machinability of tungsten carbides in orthogonal cutting with diamond-coated tools

Michael Ottersbach[a]*, Wei Zhao[a,b]

[a]*Fraunhofer Institute for Production Technology IPT, Steinbachstrasse 17, 52074 Aachen, Germany*
[b]*Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, 210016 Nanjing, China*

* Corresponding author. Tel.: +49 241 8904 451; fax: +49 241 8904 6451. *E-mail address:* Michael.Ottersbach@ipt.fraunhofer.de

Abstract

A trend in the tool and die making industry is seen towards using highly wear-resistant and extremely hard dies for stamping and forming operations, which are made of tungsten carbides. The limiting factor to manufacture such dies is the poor machinability of these materials. In this paper orthogonal cutting tests on different tungsten carbides with diamond-coated tungsten carbides tools were carried out. It was observed that ductile cutting of tungsten carbides is possible. The influence of different tungsten carbide grades on specific cutting forces with variable process parameters was evaluated in this paper.

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Keywords: Cutting; Carbides; Diamond coating

1. Introduction

Tungsten carbides are important materials for the production of cutting tools, molds and dies due to their high hardness and excellent resistance against mechanical loadings and wear [1]. Especially in the die and mold making industry, more and more dies are made of tungsten carbides instead of hardened steels or powder metallurgical steels in order to fulfil the market demands of long tool life time. The excellent mechanical properties like a more than two times higher Young`s modulus compared to steel and hardness values of over 2000 HV lead to extremely poor machinability of tungsten carbides. These material properties are the main limitation for the wide use of tungsten carbides. Presently, grinding, polishing, electrical discharge machining (EDM) and electrochemical machining (ECM) are the only mentionable machining technologies. However, these processes are limited in their productivity and geometrical flexibility [1-2]. Therefore cutting processes, especially milling, which are highly flexible and productive in the same way, have a high potential to improve the manufacturing of dies and molds made of tungsten carbides.

Presently it is not possible to apply milling processes to tungsten carbides. The reason is the high thermo-mechanical loading on the tool, which leads to fast and non-predictable failures of the coating and tool substrate when machining tungsten carbides [3-5]. The consequence is that manufacturing of tungsten carbide dies is not economical with the actual milling tool and process technology.

In the past 20 years many researches were working on the topic of machining tungsten carbides with defined cutting edges. LIU et al. [5] studied the micro- and nanoscale ductile cutting of tungsten carbide with CBN cutting tools. They validated that ductile cutting could be achieved when the undeformed chip thickness was below a certain critical value. High precision turning of fine grain sized tungsten carbides was investigated by BERTALAN and by MOELLER for coarse grain sized tungsten carbides [6-7]. The ultrasonic elliptical vibration cutting (UEVC) method was analyzed by SUZUKI et. al., NATH et. al and ZHANG. They found out that by ultrasonic vibrations the cutting process can be improved compared to conventional machining. With this method it was possible to increase the maximum uncut chip thickness for ductile cutting of brittle materials [8-10].

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ARIF et al. developed an analytical model to determine the critical uncut chip thickness for finishing a crack-free surface on tungsten carbides by micro milling [11-12]. Furthermore, NAKAMOTO et al. [13] and ZHAN et al. [14] studied the influence of PCD tool wear on the surface roughness of tungsten carbides in micro milling.

First tests in milling with different cooling concepts of thermally sprayed tungsten carbides with tools made of thickfilm CVD-diamond were analyzed by NEUGEBAUER. The tools failed unreproducible and mainly due to brittle chippings on the rake face. [15]

However, the mentioned researches showed that ductile cutting of tungsten carbide is possible, but limited to very small uncut chip thickness of a few micrometers. A transfer to milling operations of dies and molds is therefore limited due to fast tool failures, which are resulting from the poor combination of toughness and hardness of the tools. First tests showed that the combination of tough tungsten carbide substrates with hard CVD-diamond coatings can be a process enabler for milling of tungsten carbides. Actually just rare information and knowledge exist on milling of tungsten carbides.

The motivation of this paper is to conduct systematical analyses in orthogonal cutting tests on different tungsten carbide grades with diamond coated tungsten carbide tools. The aim is to get fundamental knowledge about the machinability of the hard to machine materials tungsten carbides when varying the process and material parameters. In this first investigation the chip formation and the specific cutting forces are evaluated. With the generated knowledge it will be possible to optimize milling tool's geometry and to design economical high performance milling processes for tungsten carbides. It will be possible to significantly improve the actual process chain for manufacturing dies and molds of tungsten carbides by the substitution of EDM and grinding by milling.

2. Experimental setup

The orthogonal cutting tests were carried out on a specially developed test bench. By this it is possible to obtain fundamental knowledge about the machinability of difficult-to-cut materials like tungsten carbides (see Fig. 1). The test bench is driven by hydrostatic linear direct drives and equipped with a Kistler force measurement unit, a high velocity video camera and a thermal video camera [16].

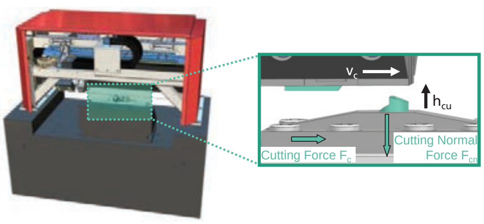

Fig. 1: Setup of test bench

The analyzed tools are made of submicron grain sized tungsten carbide (average grainsize 0.4 µm) coated with a multilayer CVD diamond. To ensure reproducibility of the tests the geometry of the cutting edge of the tools is measured with an Alicona Infinite Focus 4G measurement system (see Table 1).

Table 1. Properties of cutting tools and coating material

Properties	Rake angle (°)	Clearance angle (°)	Cutting edge radius (µm)	Coating thickness (µm)	Coating hardness (HV0.05)
	0	15	19±2	20	10,000

In total two different tungsten carbide grades were machined. The focus in this analysis was to investigate the influence of the variation of the cobalt content on the machinability. Thus fine grain sized tungsten carbides were chosen with a cobalt content varying from 17.5 to 11.8 weight percent. To define the average grain size, cross sections of both materials were taken and afterwards analyzed by a linear structure analysis (see Fig. 2). The average measured grain size of the tungsten carbides was 0.7 µm in both cases. The composition and the resulting physical properties can be found in Table 2 and Table 3.

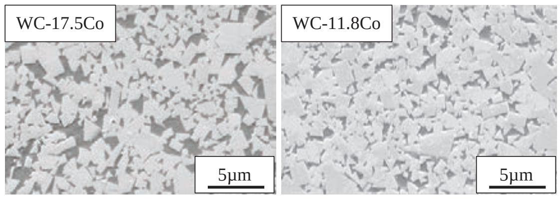

Fig. 2. Cross sections of the investigated tungsten carbides

Table 2. Composition of the workpiece materials

Grade \ **Composition**	WC (wt.-%)	Co (wt.-%)	Other (wt.-%)	Average measured grain size (µm)
WC-17.5Co	80.3	17.5	2.2	0.7
WC-11.8Co	87.0	11.8	1.2	0.7

Table 3. Physical properties of the workpiece materials

Grade \ **Properties**	Hardness HV10	Transverse rupture strength MPa	Fracture toughness $MPa{\bullet}m^{0,5}$	Density g/cm^3	Young's modulus GPa
WC-17.5Co	1150	3300	15	13.56	480
WC-11.8Co	1400	3000	12	14.15	551

For the experiments the process parameters cutting velocity v_c and uncut chip thickness h_{cu} are varied. The cutting velocities are set to the values 70 and 140 m/min and the uncut chip thickness was varied step by step to values between 1 and 30 µm. The width of cut *b*, which is given by the thickness of the specimen, is 1.22 mm. The cutting length is 20 mm. To increase the precision of the test bench, the actual uncut chip thickness is measured by a tactile measurement sensor, which measures the height of the specimen before and after each test. By subtracting both profiles the exact thickness of the removed material is calculated.

3. Results and discussion

During the experiments high velocity videos were taken. The analysis shows that ductile chips can be generated although brittle chips were expected. Fig. 3 shows the chip formation process of WC-17.5Co with the uncut chip thickness of 12 µm and cutting velocity of 140 m/min.

Fig. 3. Stationary pictures of chip formation from high velocity videos of WC-17.5Co at v_c= 140 m/min, h_{cu} =12 µm, tool 1

The pictures show clearly a ductile chip formation during the machining process. Besides the long ductile chip some small particles, which are flying away from the cutting zone, could be observed in the videos as well. These particles give hints for a brittle breakage of small pieces of the chip. The reasons for these breakages can be microdefects at the surface or areas with low cobalt, which tend to brittle material failure, which was also seen by BERTALAN in turning operations [6].

Also for the WC-11.8Co ductile mode chips were observed, but a clear difference in the chip formation was seen when decreasing the cobalt content. The chip shape is becoming more and more straight and less curved. Furthermore the chip breaks faster and leads to shorter chip segments (see Fig. 4).

Fig. 4. Stationary pictures of chip formation from high velocity videos of WC-11.8Co at v_c= 140 m/min, h_{cu} =10 µm, tool 1

It can be observed that the amount of brittle pieces during the cutting process is increased compared to the WC-17.5Co. This leads to the assumption, that the ductile formation of the chip mainly takes place in the cobalt phase of the tungsten carbide. The WC-grains are not able to pass a ductile deformation regime, which finally leads to micro breakage and brittle fracture of the machined material. These phenomena have to be further investigated in detailed metallographic analyses of the machined chips and the rim zone of the workpiece afterwards.

After each cut the condition of the tools` cutting edge is controlled with a Keyence measurement microscope. The tools show no damage or defects after the cuts. Just a very thin light shining area was seen at the cutting edge, which indicates the area of contact with the workpiece (see Fig. 5). The cutting edge is still covered with the diamond coating and does not show chippings or breakages. This confirms that the tools` substrate-coating combination can withstand the thermo-mechanical loadings while machining tungsten carbides. In former tests the tools mainly fail due to chipping of the coating and cutting edge brakeage.

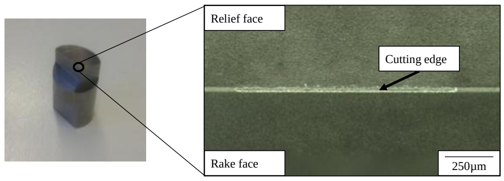

Fig. 5. Condition of cutting edge after machining tungsten carbide (WC-11.8Co, v_c=140 m/min, h_{cu}=10µm)

To evaluate the machinability of different tungsten carbides the specific cutting forces k_c and k_{cn} were selected as the key assessment factors [17]. The evaluations were done for the cutting force F_c as well as for the cutting normal force F_{cn}. The resulting k_c- and k_{cn}- curves for the cutting velocity 70 m/min (Fig. 6) and 140 m/min (Fig. 7) are shown for the two tungsten carbide grades.

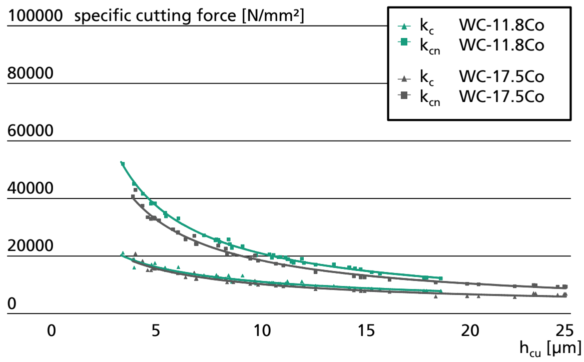

Fig. 6. Specific cutting forces for different tungsten carbide grades at v_c = 70m/min

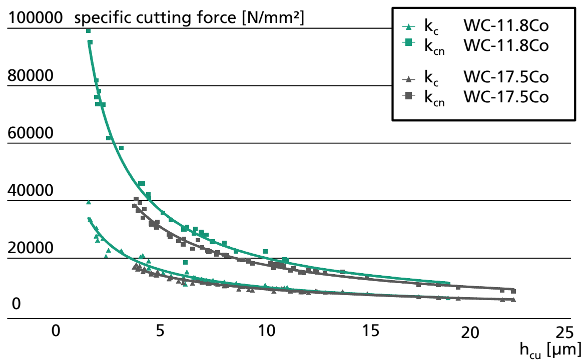

Fig. 7. Specific cutting forces for different tungsten carbide grades at v_c = 140m/min

It can be observed that the specific cutting normal force is significantly higher than the specific cutting force in the analyzed parameter field. All graphs decrease rapidly until an average uncut chip thickness of around 4-6 µm. From this point on the gradient of the curve is clearly lower. The strong decrease of the specific cutting forces up to an uncut chip thickness of 4-6µm indicates a ploughing and squeezing dominated machining process, where no defined or ductile material removal is possible. This value is around the ratio r_β/h_{cu}=0,3, which was also found by XU as a value for the minimum uncut chip thickness for alloyed steels [6, 18]. The effect of material deformation was also seen in the high velocity videos for the uncut chip thickness less than 6 µm.

The analysed process parameters in combination with the cutting edge rounding are resulting in a high negative effective rake angle γ_{eff} of the tool, which is considerably lower than the rake angle of the tool itself. This effect leads to high hydrostatic pressure in front of the cutting edge. It can be a possible reason to explain the ductile regime chip formation up to high uncut chip thicknesses, which were realized in the experiments [19].

The maximum uncut chip thickness, for which ductile cutting was seen, is in strong correlation with the cobalt content of the tungsten carbides. For the WC-17.5Co ductile chips up to h_{cu} = 25 µm (v_c = 70m/min) was observed, whereas for WC-11.8Co just 18 µm could be realized under the same process parameters. By further increasing the uncut chip thickness just brittle chips and tool failures were seen.

The effect of the cutting velocity on the specific cutting forces is relatively low. The values for specific cutting and cutting normal force are close to each other. Especially at higher uncut chip thickness (>10 µm) the difference in the cutting forces is not significant. For lower uncut chip thicknesses higher cutting velocities seems to be a process enabler for the two investigated tungsten carbides. In this range the specific cutting forces are less for the cutting velocity of 140 m/min compared to 70 m/min.

4. Conclusions

Orthogonal cutting experiments on two tungsten carbides with diamond coated tungsten carbide tools were carried out in this work. The main conclusions are as follows.

- High velocity videos of the cutting process clearly showed ductile cutting with continuous chips in the given range of cutting parameters. It was possible to achieve ductile chips up to 25 µm for the WC-17.5Co, which is significantly higher than in former investigations.
- For the WC-11.8Co the maximum uncut chip thickness, for which ductile chips were seen and no damage to the tools appear, is around 18 µm and significantly lower compared to the WC-17.5Co. The minimum uncut chip thickness for both materials was found in the range of 4-6 µm and correlates with the value r_β/h_{cu} = 0,3, which is also characteristical for different other materials like e.g. hardened alloys and steels.
- A clear difference in the chip formation of the investigated tungsten carbides was seen. With increasing cobalt content the length of the chips and the chip curvature increase.
- The specific cutting normal forces are higher than the cutting forces in the evaluated processes. The k_c- and k_{cn}-factors can finally be used for the definition of empirical force models, e.g. Kienzle or Altintas.
- Higher cutting velocities seem to be a process enabler for low uncut chip values, because of reduced cutting forces in the experiments.

To evaluate the machinability in more detail, the chip formation mechanisms, the surface integrity and the temperature in the cutting zone will be analyzed in future research. Furthermore the effect of different tool geometries will be considered as well. The gained knowledge will be transferred to real milling applications to optimize the tools geometry and the process parameters when milling tungsten carbides.

Acknowledgements

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